Deep Space Weak Signal Hardware and Software for CubeSats

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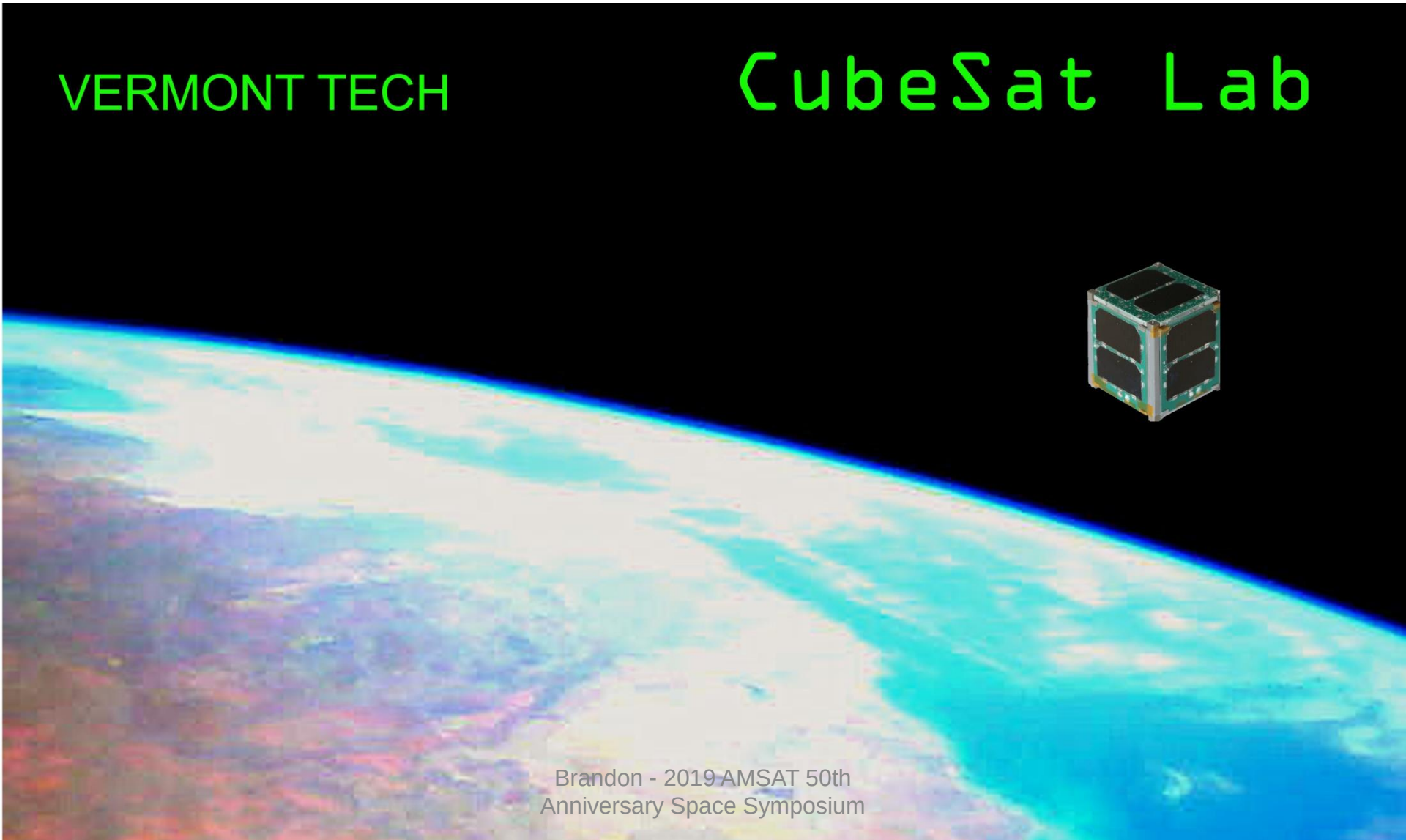
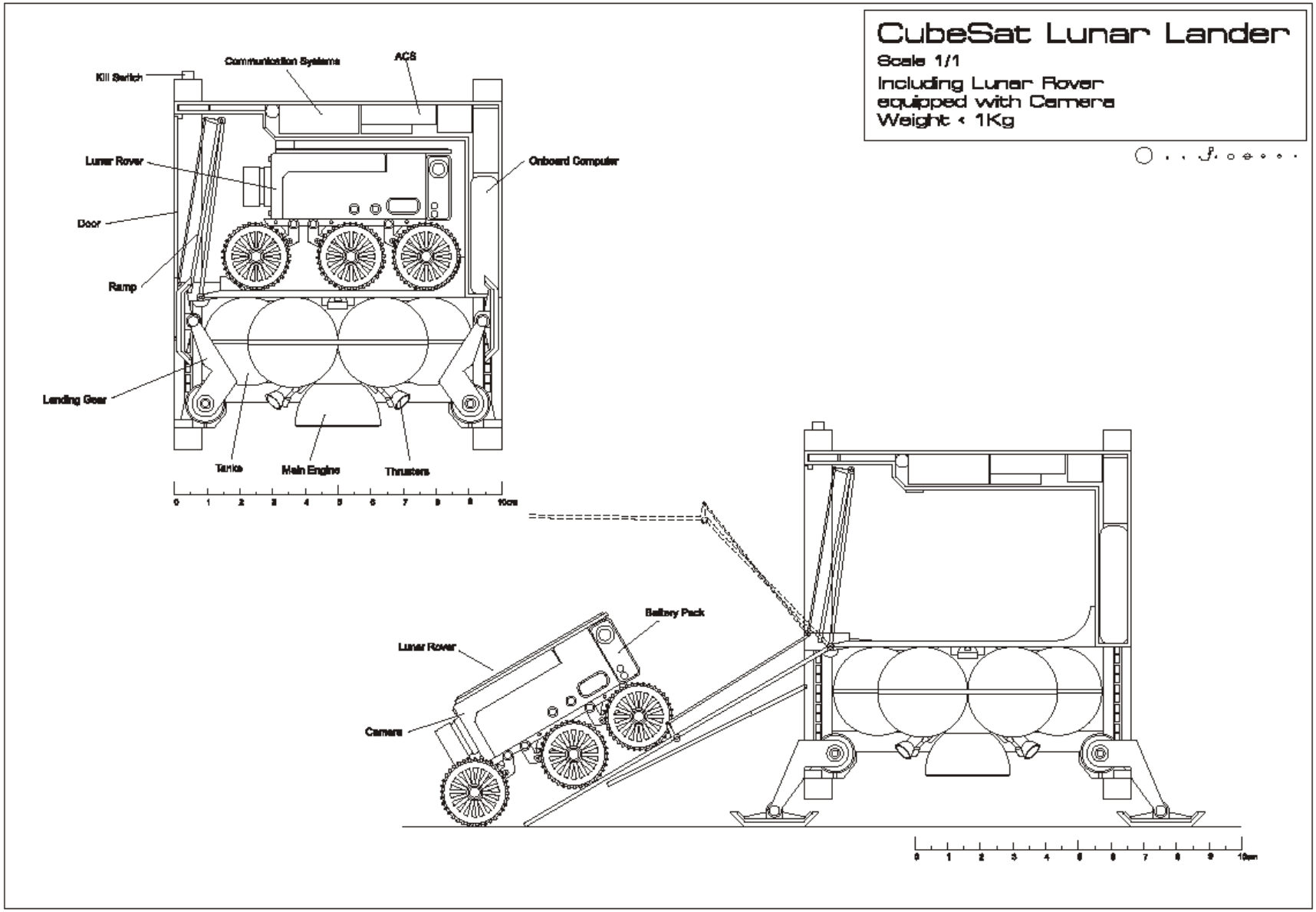
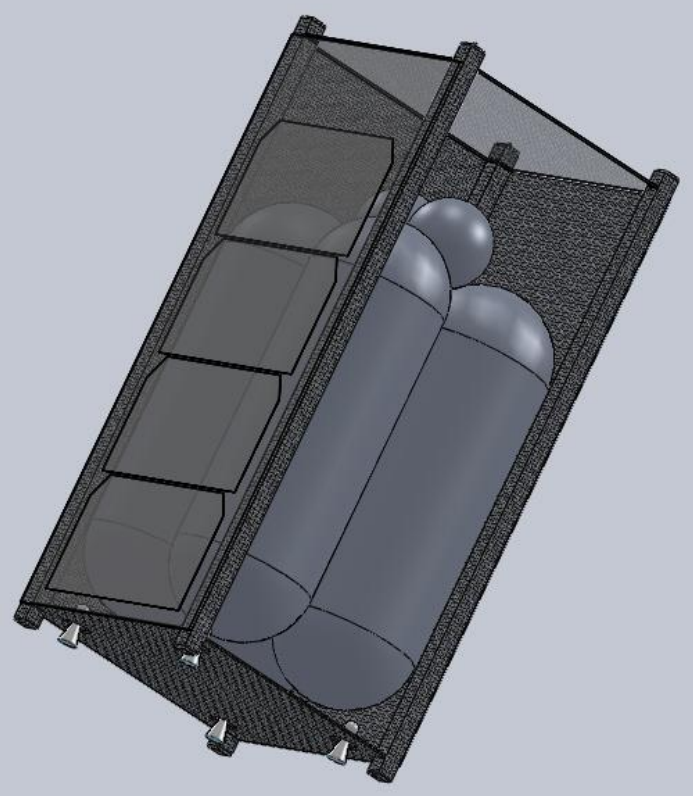


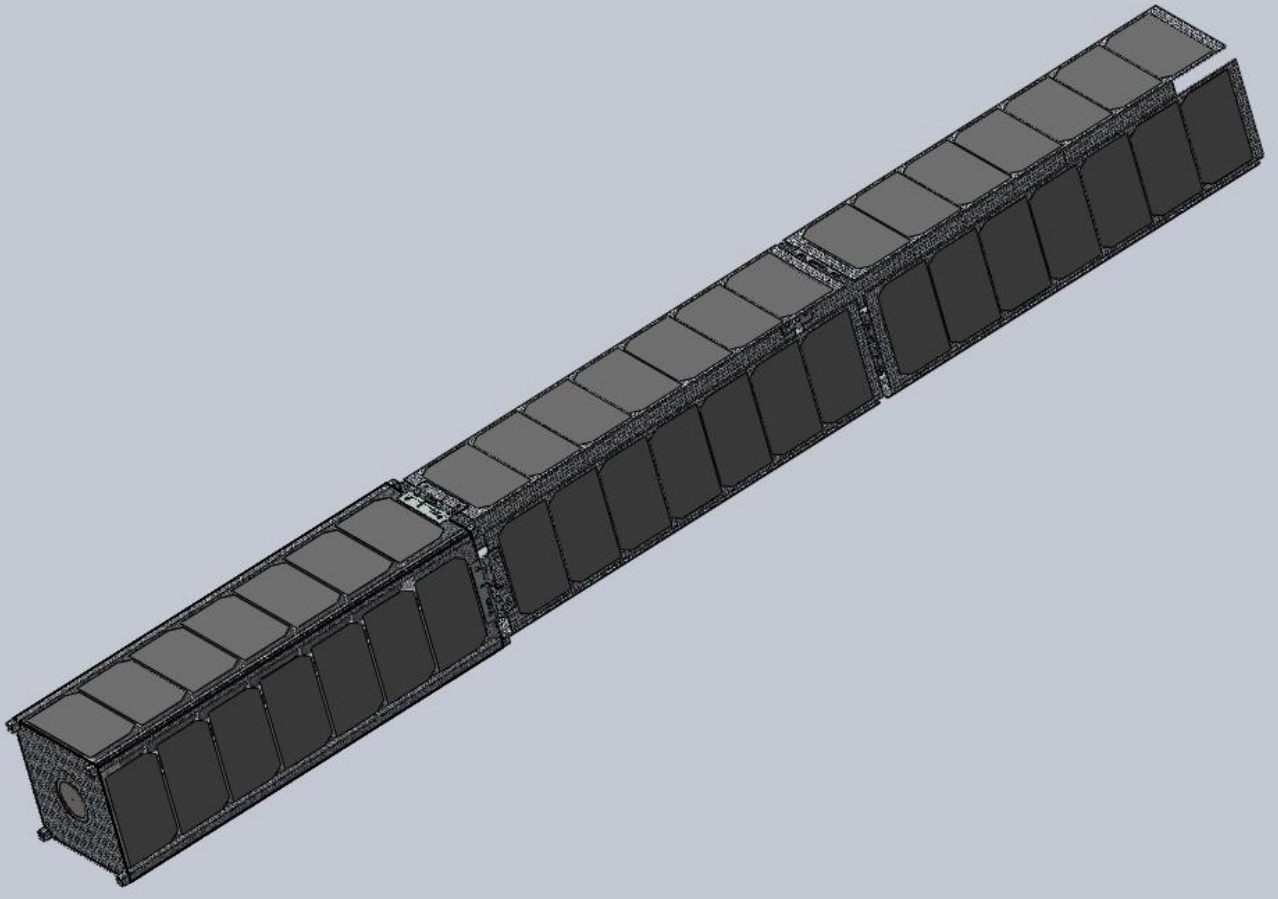

CubeSat Lunar Lander
Scale 1/1
Including Lunar Rover
equipped with Camera
Weight < 1Kg
Kill Switch
Communication Systems
ACS
Lunar Rover
Onboard Computer
Door
Ramp
Landing Gear
Tanks
Main Engine
Thrusters
Battery Pack
Lunar Rover
Camera

I was an invited speaker (of the Moon Society) to the Space Development Conference, along with Scott Carpenter, John Glenn and Buzz Aldrin. I spoke about sending CubeSats to the Moon.

Monopropellant 2U Booster CubeSat



3U Ion Drive CubeSat with PV panels



Monopropellant hydroxyl-ammonium nitrate Thruster, Busek BGT-X5, 0.5N, 225s ISP

Vermont Lunar CubeSat

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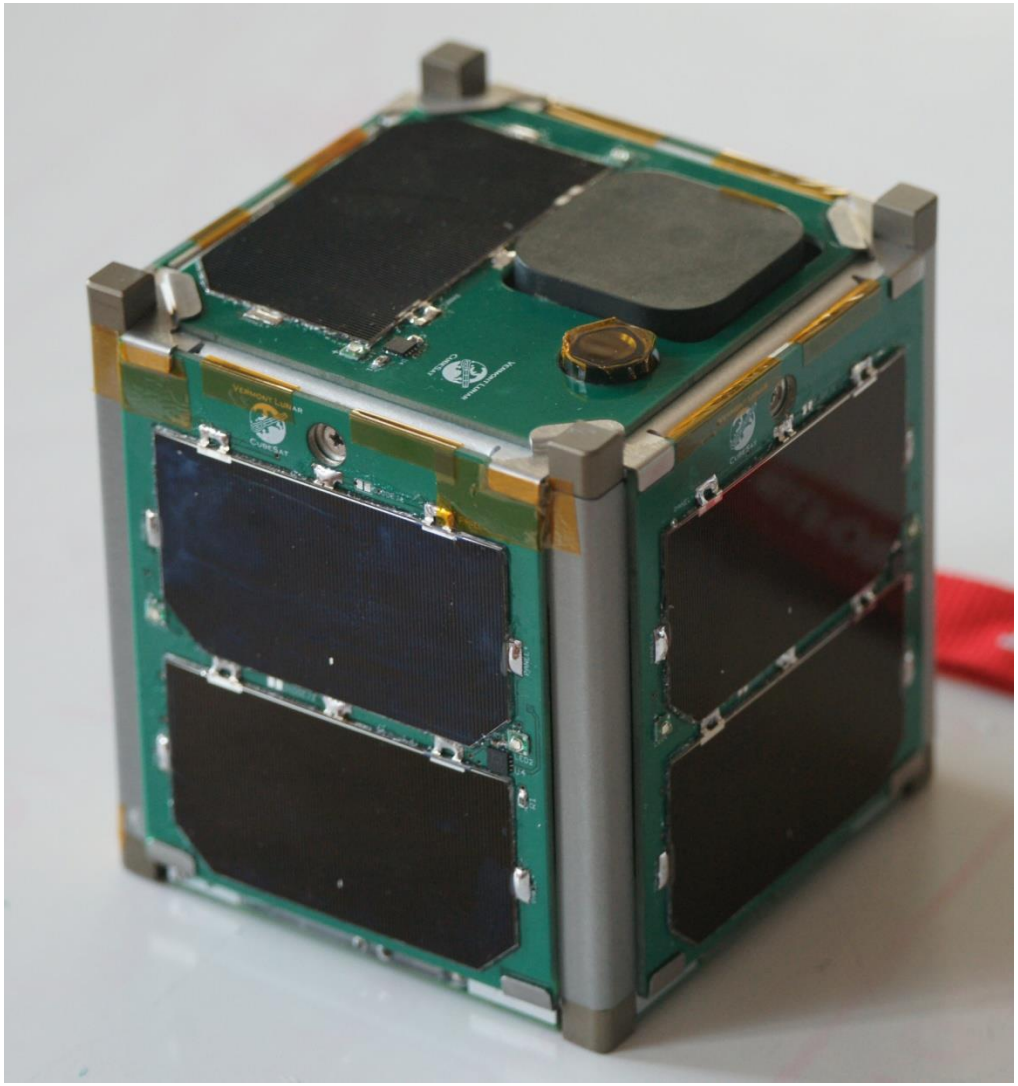


Launch, November 19, 2013

Vermont Lunar CubeSat (10 cm cube, 1 kg)

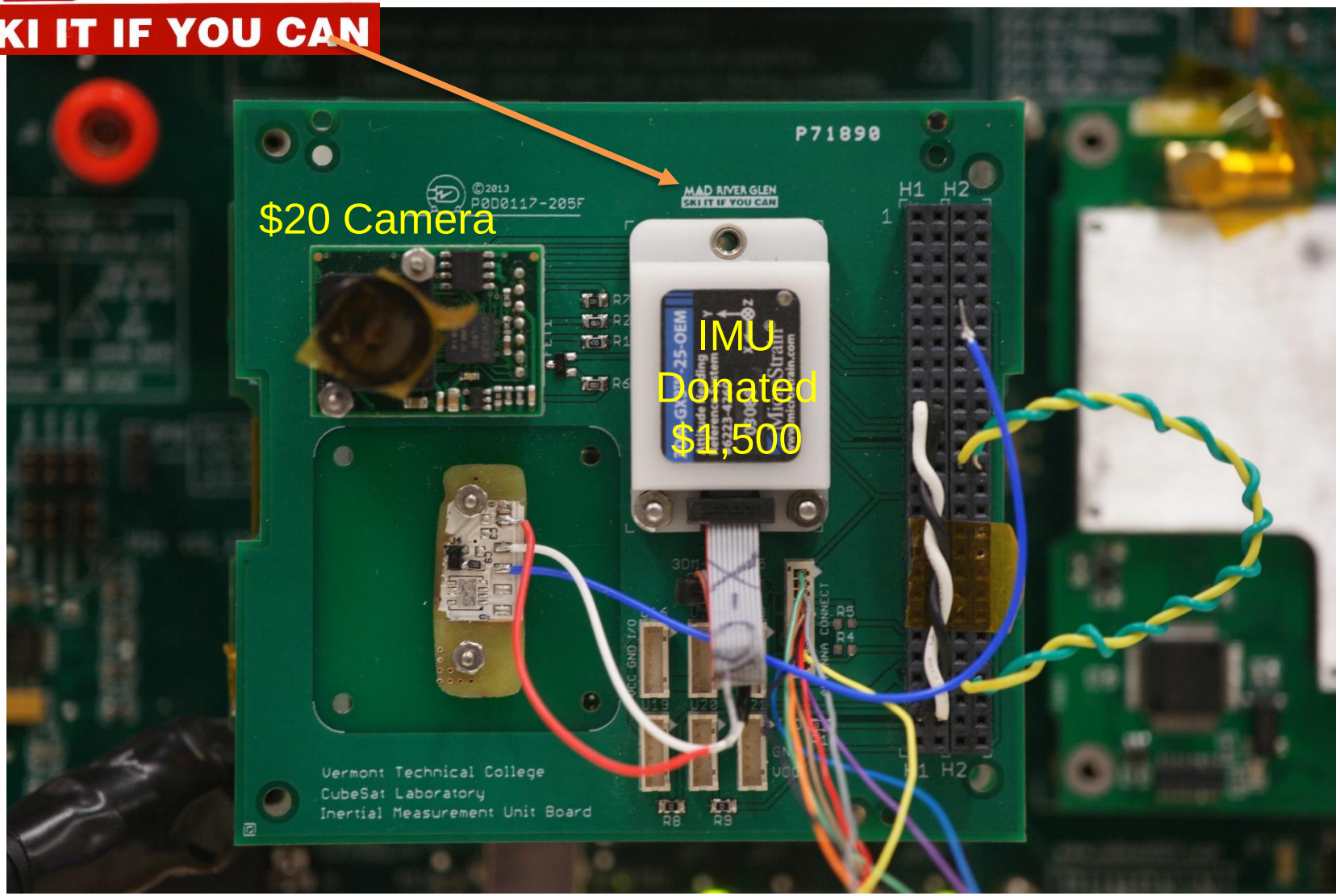
Vermont Lunar CubeSat

VERMONT TECH

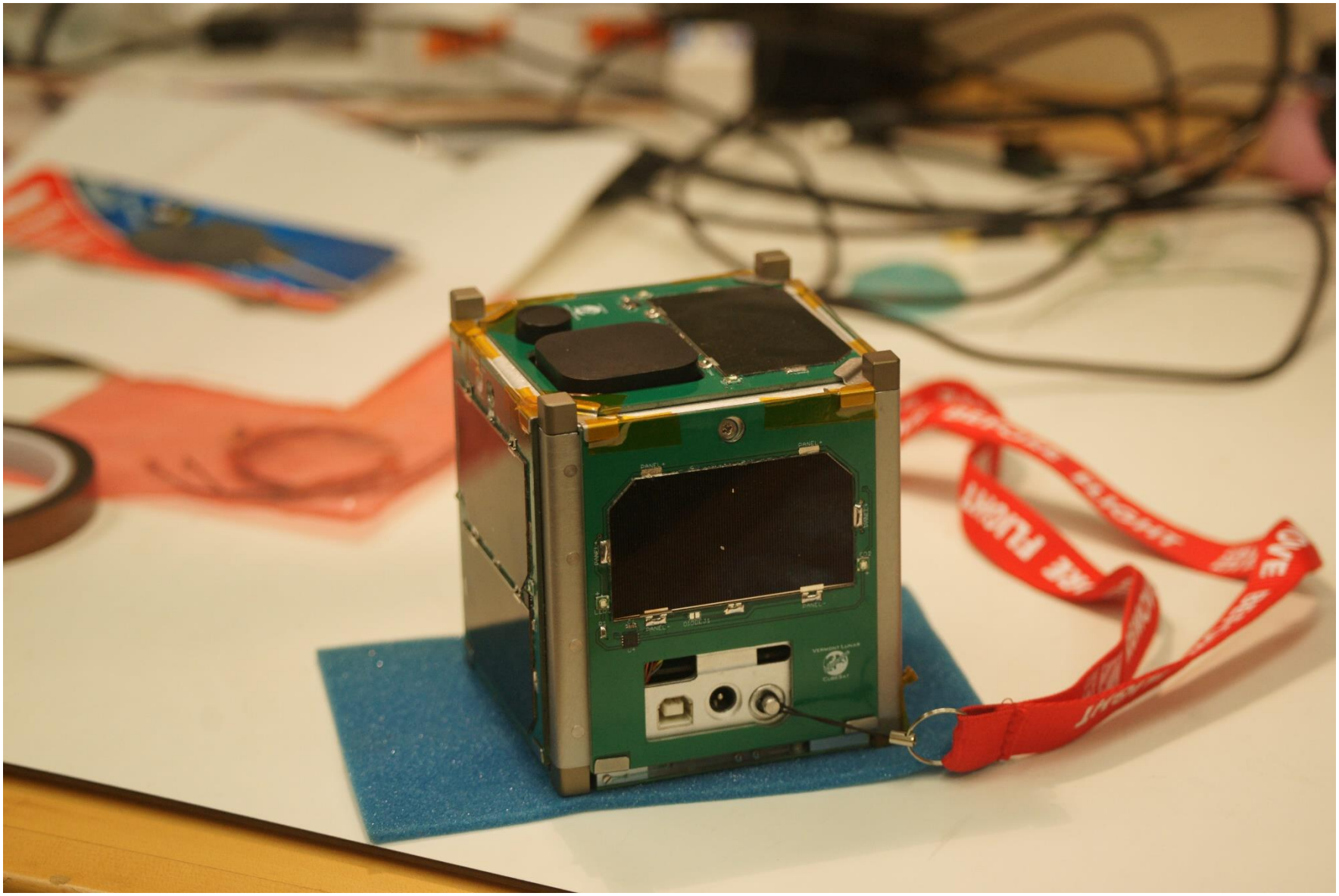
It worked until our reentry on November 21, 2015:

- We completed 11,071 orbits.
- We travelled about 293,000,000 miles, equivalent to over 3/4 the distance to Jupiter.
- Our single-unit CubeSat was launched as part of NASA's ELaNa IV on an Air Force ORS-3 Minotaur 1 flight November 19, 2013 to a 500 km altitude, 40.5^{o} inclination orbit and remained in orbit until November 21, 2016. **It is the only one of the 12 ELaNa IV university CubeSats that operated until reentry, the last one quit 19 months earlier.**
- We communicated with it the day before reentry
- We were the first university satellite from New England
- We were the only successful university satellite on the east coast until this year
- **Follow our project at cubesatlab.org**

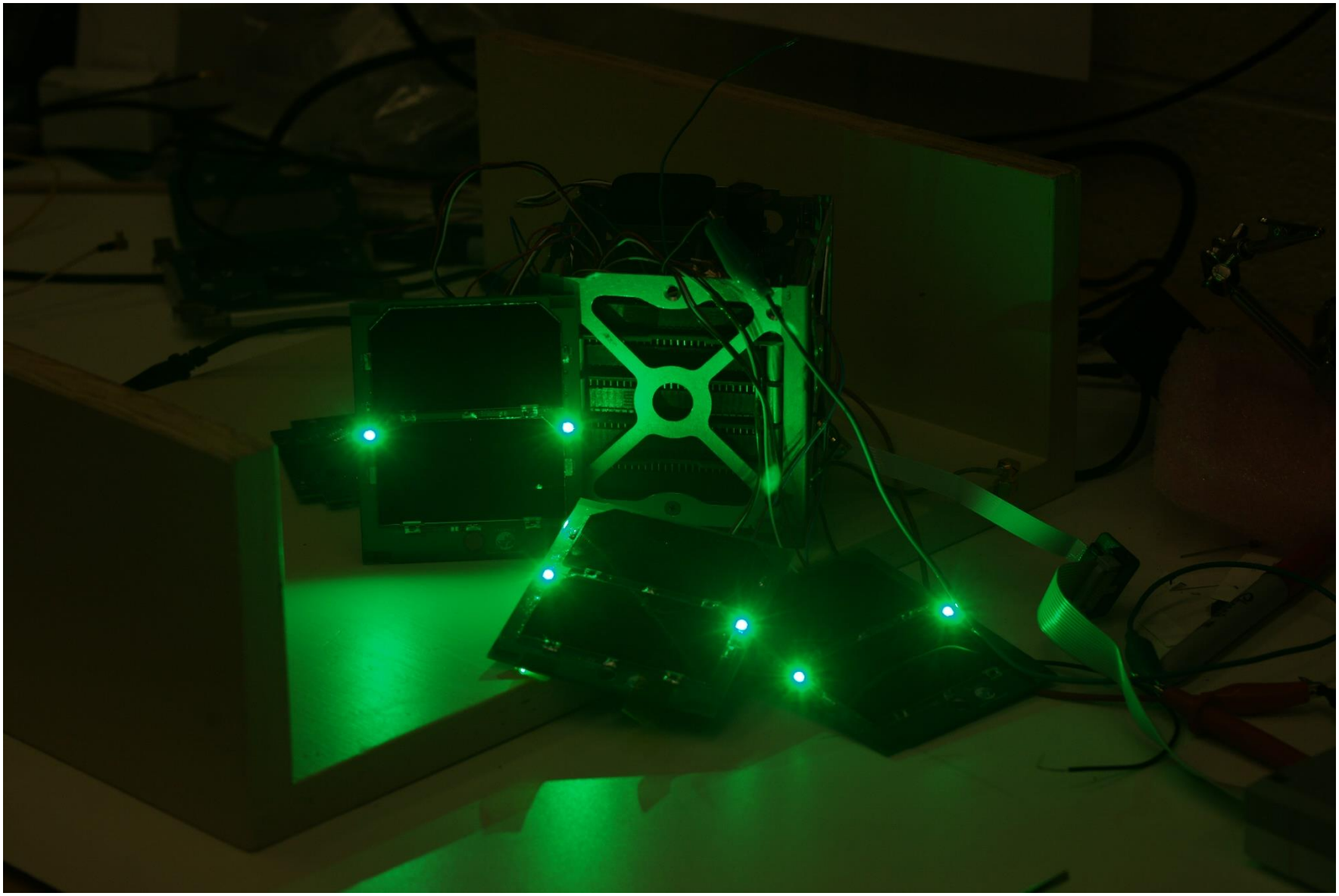
Camera, inertial measurement unit.



Assembled Vermont Lunar CubeSat



Testing the LEDs



ELaNa IV Launch Minotaur 1 – Wallops Island November 19, 2013, 8:15 PM

I am with my two software students, Dan and India, and my son, Jack. First two stages are Minuteman II, third and fourth stages are Pegasus second and third stages

Missing Malaysian airliner

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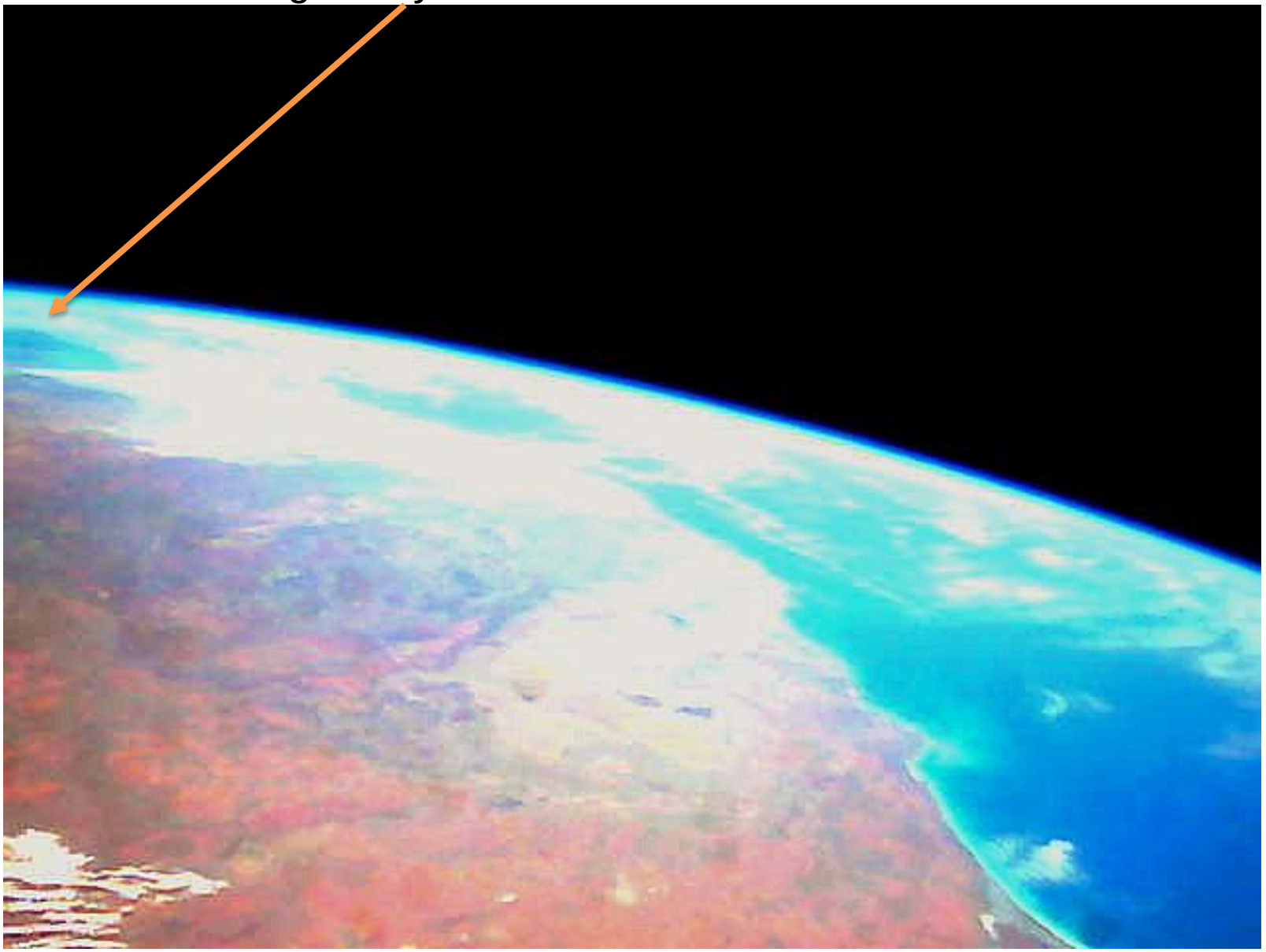
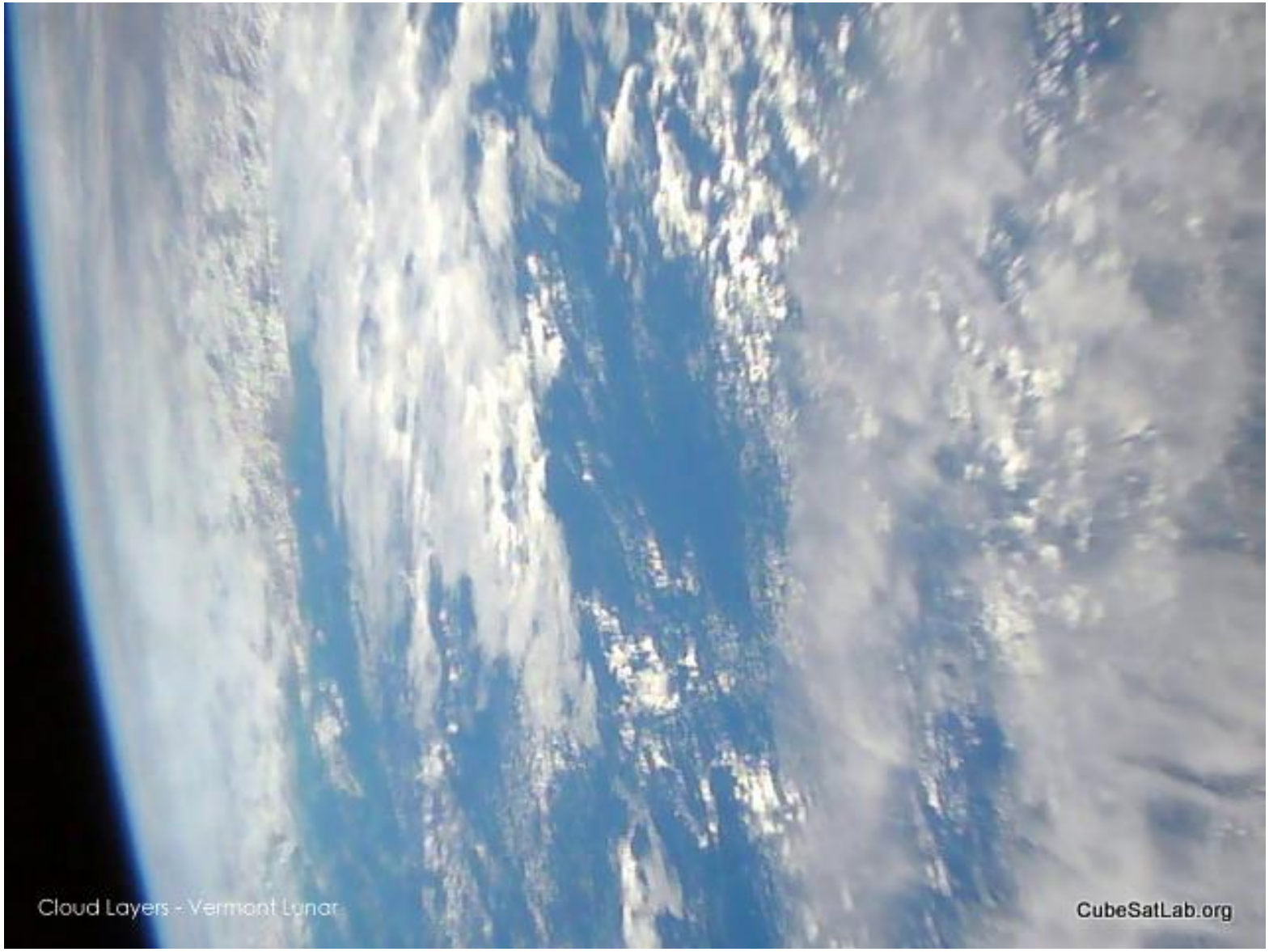
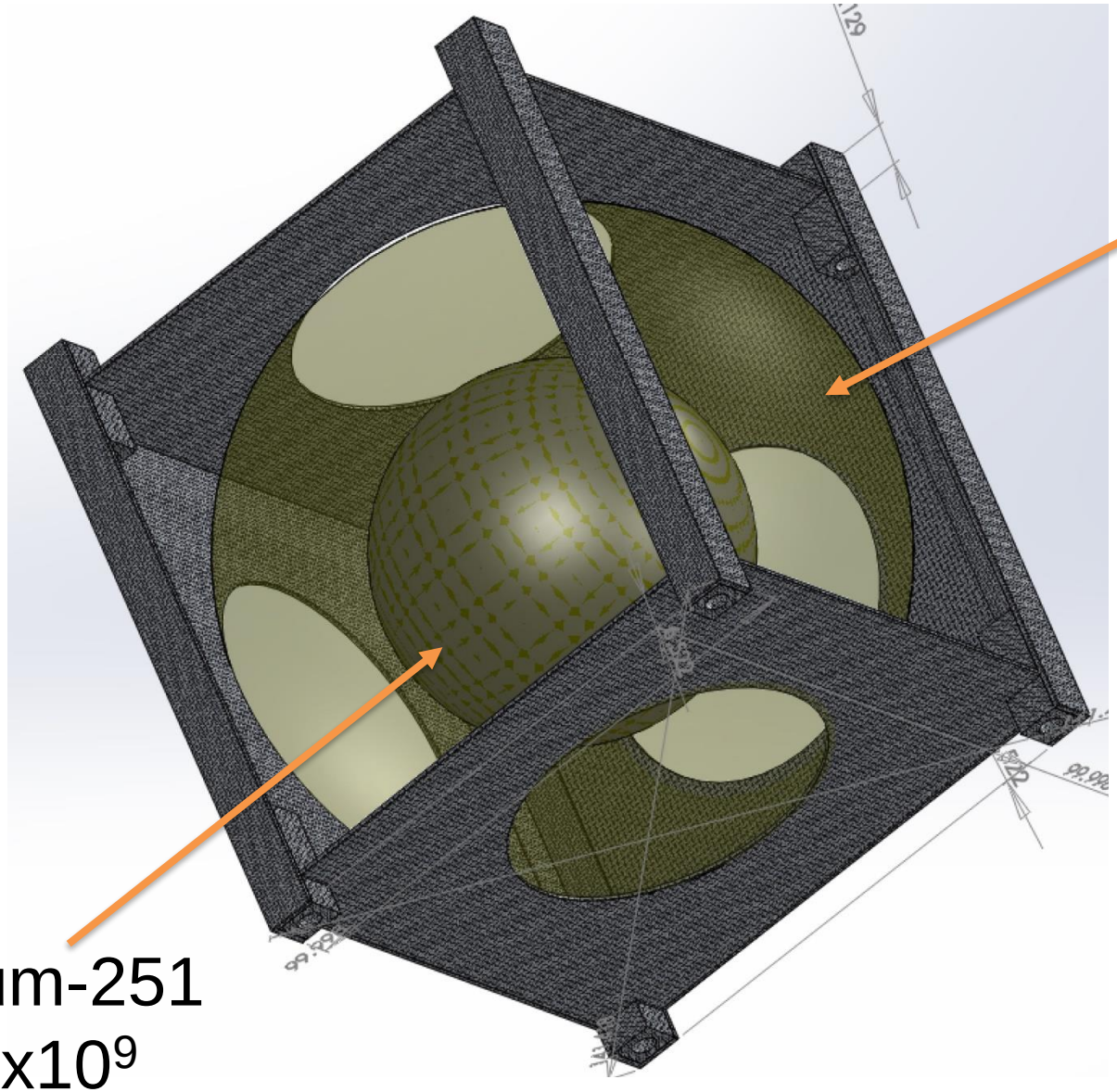


Our first picture of Earth, The North coast of Western Australia



Clouds over the ocean, June 2015, 19 months after launch.

Large Area Orbital Debris Mitigation



Californium-251
5 kg, $\$50 \times 10^9$

Why We Use SPARK/Ada

ELaNa IV lessons for CubeSat software:

- NASA's 2010 CubeSat Launch Initiative (ELaNa)
- Our project was in the first group selected for launch
- Our single-unit CubeSat was launched as part of NASA's ELaNa IV on an Air Force ORS-3 Minotaur 1 flight November 19, 2013 to a 500 km altitude, 40.5^{o} inclination orbit and remained in orbit until reentry over the central Pacific Ocean, November 21, 2016, **after two years and two days. Eight others were never heard from, two had partial contact for a few days, and one worked for 4 months.**
- The Vermont Lunar CubeSat tested components of a Lunar navigation system in Low Earth Orbit

Deep Space Enabling Technologies

- Spiral Thrusting for 3-axis angular momentum control with a two axis thruster, completed.

- JT-65 Weak Signal Radio Protocol for deep space communication without the DSN, just started.

- Extremely high reliability software, CubedOS, SPARK/Ada, ongoing work.

Vermont Lunar CubeSat *SPARK 2005* software

- 5991 lines of code
- 4095 lines of comments (2843 are SPARK annotations)
- A total of 10,086 lines (not including blank lines)
- The Examiner generated 4542 verification conditions
- All but 102 were proved automatically (98%)
- We attempted to prove the program free of runtime errors
- Which allowed us to suppress all checks
- The C portion consisted of 2239 lines (including blank lines), mostly SD card driver we purchased
- Additional provers in SPARK 2014 would improve this

Language Comparison

UK Ministry of Defense C-130J software study:
The anomalies per 1,000 lines of code (average):

- **for C was 97**
- **for Ada 95 was 25**
- **for SPARK/Ada 95 was 4**

Newer Tokeneer project (for NSA)

- **For SPARK/Ada 2005 was 0.4**

Productivity of 38 lines of code per programmer day (about what our student achieved, also), compared with 10 to 12 lines of code when using C.

We are now using the even newer SPARK/Ada 2014

Language Comparison

Real world data – No reason not to use SPARK/Ada

- If your student programmers do not know SPARK/Ada, it takes about two weeks to become productive
- SPARK/Ada productivity of 38 lines of code per programmer day, compared with 10 to 12 lines of code when using C
- After three weeks, the new SPARK/Ada programmer has caught up with the C programmer
- For a 10,000 line program, the SPARK/Ada programmer would finish in 1.09 years (4 errors)
- For a 10,000 line program, the C programmer would finish in 3.33 years (970 errors)

Mars Science Laboratory Sol-200 Memory Anomaly

- Six months after landing on Mars, uncorrectable errors in the NAND flash memory led to an inability of the Mars Science Laboratory (MSL) prime computer to turn off for its normal recharge session.
- This potentially fatal error was apparently due to two pieces of its C software having pointers which pointed to the same memory. Curiosity has about 3.5 MLOC written in C. (One would expect about 35,000 errors, they had corrected about 1,500 as of two years ago)
- SPARK/Ada would have prevented this almost fatal error in a 2.5 billion dollar spacecraft.

Ariane 5 initial flight failure:

Good

Bad, 37 seconds later

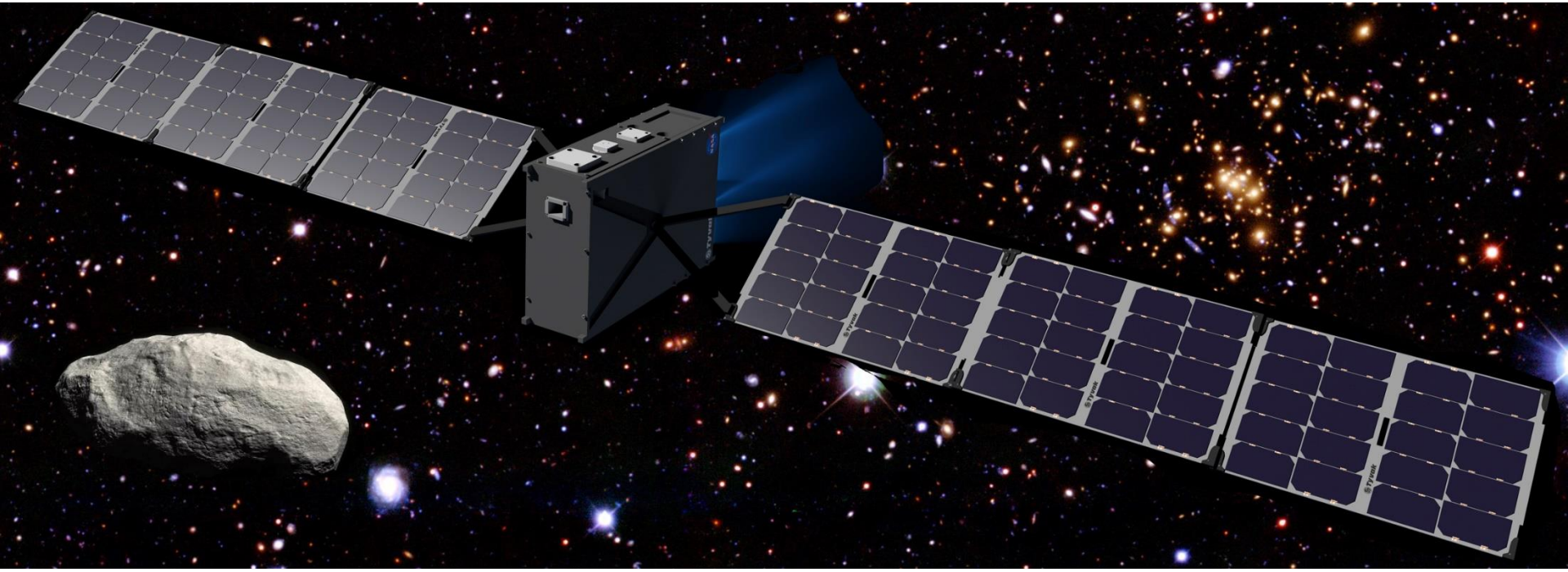
Ariane 5 initial flight failure:

- Software reused from Ariane 4, written in Ada
- The greater horizontal acceleration caused a data conversion from a 64-bit floating point number to a 16-bit signed integer value to overflow and cause a hardware exception.
- “Efficiency” considerations had omitted range checks for this particular variable, though conversions of other variables in the code were protected.
- The exception halted the reference platforms, resulting in the destruction of the flight.
- Financial loss over $500,000,000.
- SPARK/Ada would have prevented this failure

Boeing 787 generator control computer:

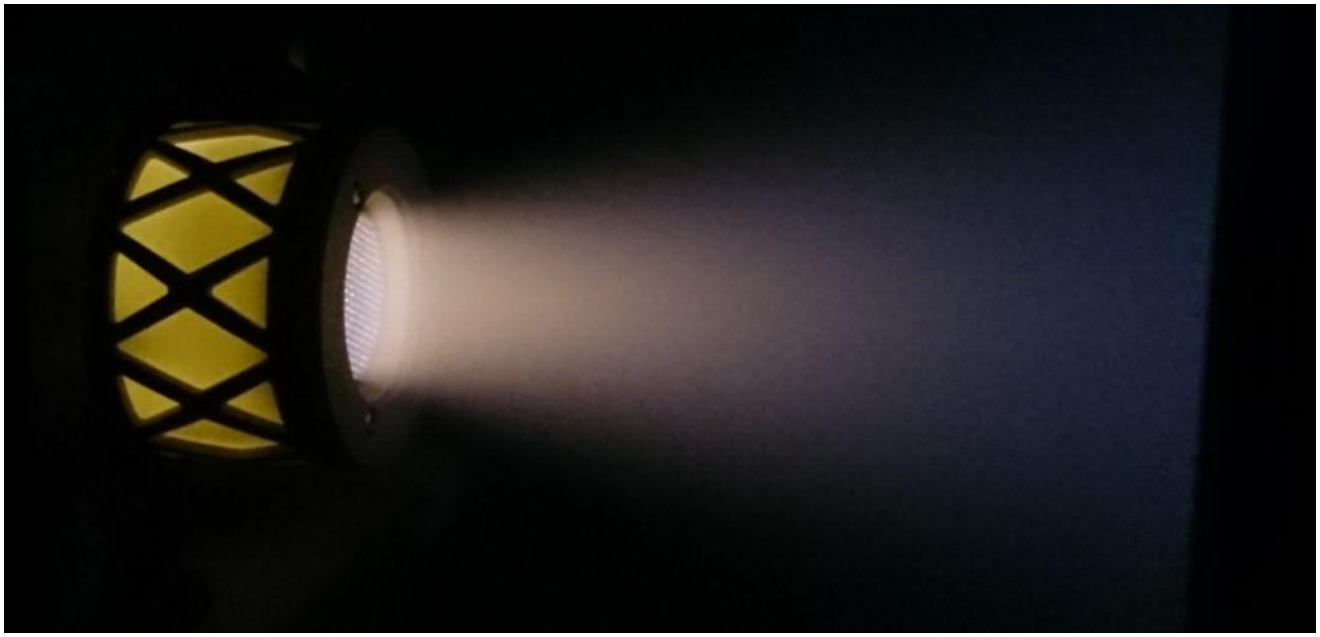
- There are two generators for each of two engines, each with its own control computer programmed in Ada (Airbus Rolls Royce controllers are in SPARK)
- The computer keeps count of power on time in **centiseconds** (used by stopwatches) in a 32 bit register
- Just after 8 months elapses, the register overflows
- Each computer goes into "**safe**" mode shutting down its generator resulting in a complete power failure, causing loss of control of the aircraft
- The FAA Airworthiness Directive says to shut off the power before 8 months as the solution
- There is now a second 787 reset problem
- SPARK/Ada would have prevented both

Deep Space Application



6U CubeSat with ion thruster
Deep space mission

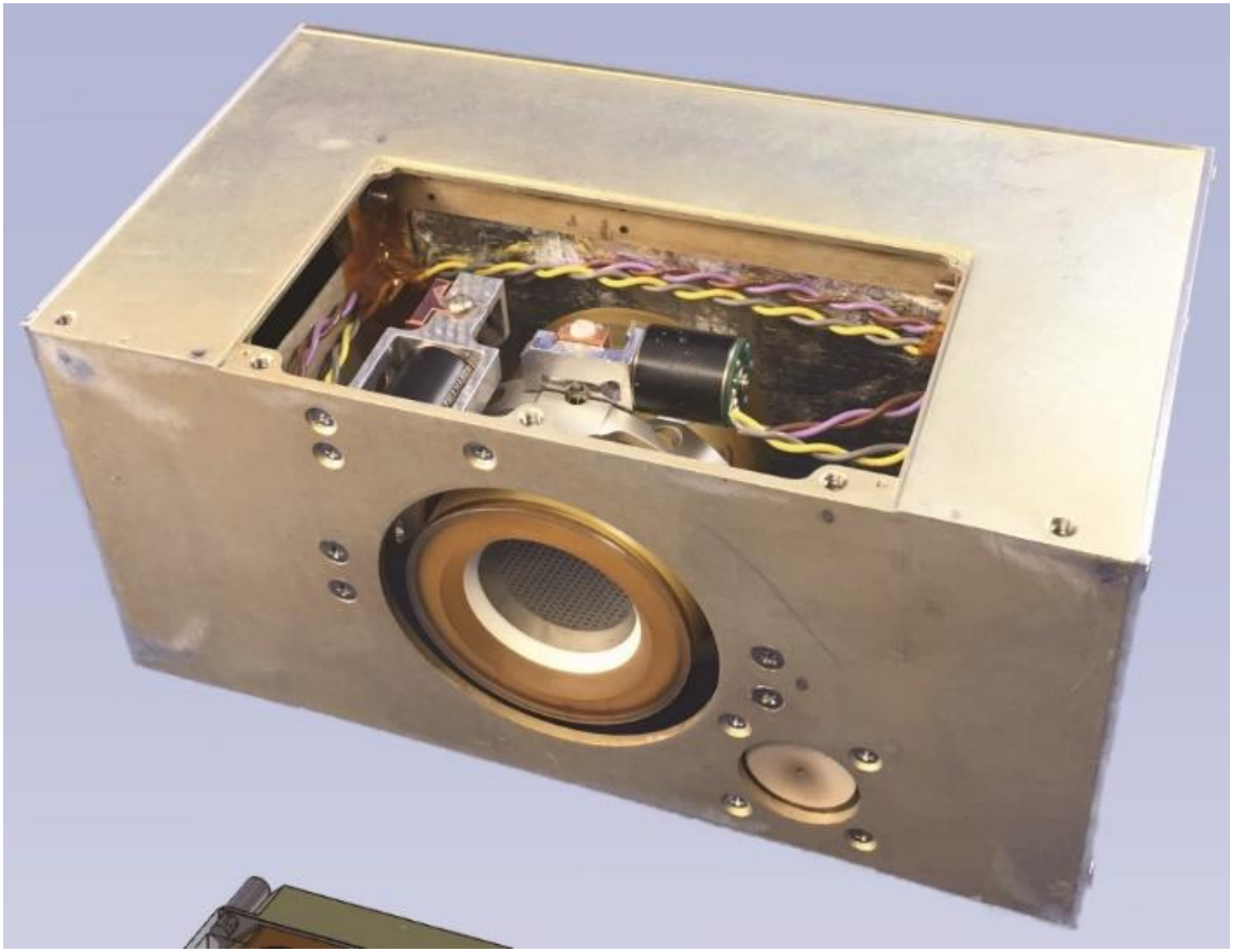
Busek Ion Thruster



BIT-3 Iodine Propellant

75W, 1.24 mN, 2.5 cm beam width, I_{SP} = 2,640
For a 6U, 14 kg spacecraft with 1.5 kg iodine:
Delta-V = 2,900 m/s

Busek Bit-3 Ion Thruster



Isp = 2,300 s, Iodine mass = 1.5kg, Δv = 2,500 m/s, 8,600 hours of thrust

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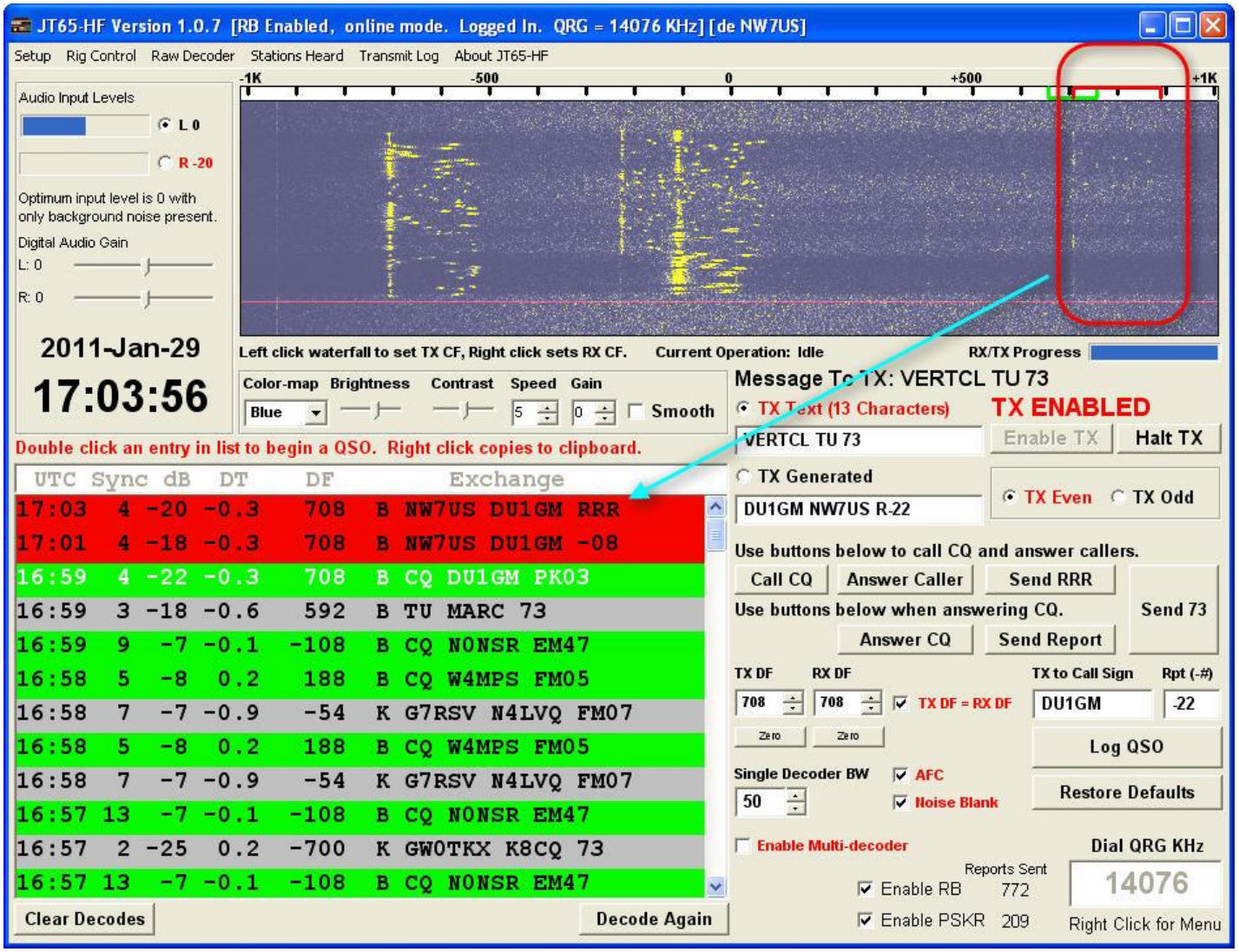
Busek BIT-3 Ion Thruster

Deep Space Network Ground Stations

The 70m Dish at Goldstone, California, X-band, 74 dB gain, normally needed for deep space communication, $6,000/hour

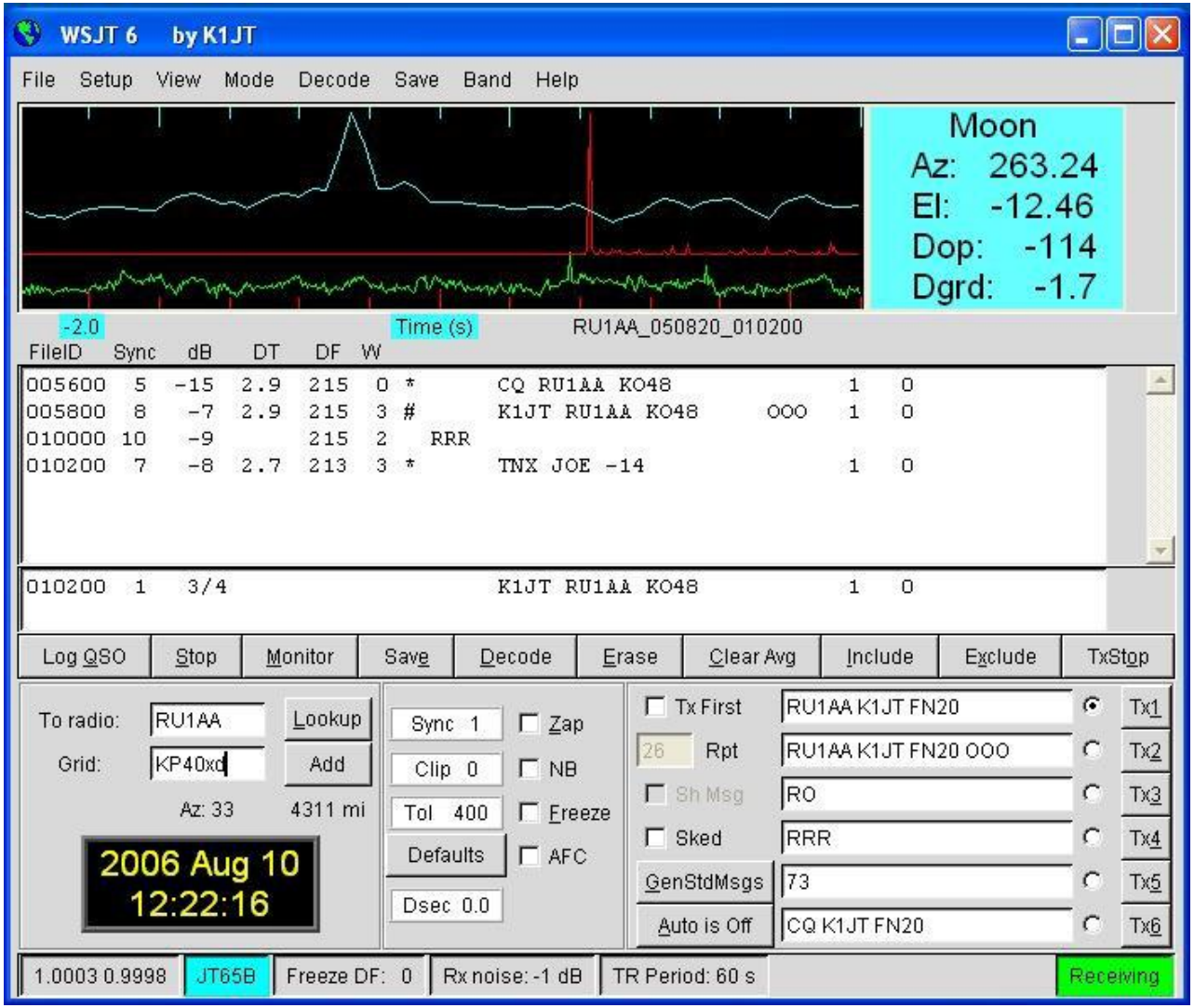
JT65 Weak Signal Protocol

Joe Taylor (my physics prof, 1993 physics Nobel Prize)


JT65-HF Version 1.0.7 [RB Enabled, online mode. Logged In. QRG = 14076 KHz] [de NW7US]
Setup Rig Control Raw Decoder Stations Heard Transmit Log About JT65-HF
Audio Input Levels
L 0
R -20
Optimum input level is 0 with only background noise present.
Digital Audio Gain
L: 0
R: 0
2011-Jan-29
17:03:56
-1K -500 0 +500 +1K
Left click waterfall to set TX CF, Right click sets RX CF.
Current Operation: Idle
RX/TX Progress
Color-map Brightness Contrast Speed Gain
Blue
Smooth
Double click an entry in list to begin a QSO. Right click copies to clipboard.
UTC Sync dB DT DF Exchange
17:03 4 -20 -0.3 708 B NW7US DU1GM RRR
17:01 4 -18 -0.3 708 B NW7US DU1GM -08
16:59 4 -22 -0.3 708 B CQ DU1GM PK03
16:59 3 -18 -0.6 592 B TU MARC 73
16:59 9 -7 -0.1 -108 B CQ N0NSR EM47
16:58 5 -8 0.2 188 B CQ W4MPS FM05
16:58 7 -7 -0.9 -54 K G7RSV N4LVQ FM07
16:58 5 -8 0.2 188 B CQ W4MPS FM05
16:58 7 -7 -0.9 -54 K G7RSV N4LVQ FM07
16:57 13 -7 -0.1 -108 B CQ N0NSR EM47
16:57 2 -25 0.2 -700 K GW0TKX K8CQ 73
16:57 13 -7 -0.1 -108 B CQ N0NSR EM47
Clear Decodes
Decode Again
Message To TX: VERTCL TU 73
TX Text (13 Characters)
TX ENABLED
VERTCL TU 73
Enable TX
Halt TX
TX Generated
DU1GM NW7US R-22
TX Even
TX Odd
Use buttons below to call CQ and answer callers.
Call CQ
Answer Caller
Send RRR
Use buttons below when answering CQ.
Send 73
Answer CQ
Send Report
TX DF
RX DF
TX to Call Sign
Rpt (-#)
708
708
TX DF = RX DF
DU1GM
-22
Zero
Zero
Log QSO
Single Decoder BW
AFC
50
Noise Blank
Restore Defaults
Enable Multi-decoder
Dial QRG KHz
Reports Sent
Enable RB 772
14076
Enable PSKR 209
Right Click for Menu

JT65 Weak Signal Protocol

Joe Taylor (my physics prof, 1993 physics Nobel Prize)



JT65 Weak Signal Protocol

Joe Taylor (my physics prof, 1993 Nobel Prize)

Each message contains 72 (378 with FEC) bits over 48 seconds

With a 3m dish, @ 9 GHz, you can reach Jupiter (4.45 AU), 663 million km at it's closed point

Calculated Performance

SNR (dB)	Channel symbols	Bits	
−18	46.9	281	10.1
−20	39.6	237	8.4
−22	31.9	191	6.9
−24	23.1	139	4.9
−26	15.5	93	3.3
−28	9.6	58	2.1

Actual Performance

Frequency (MHz)	432
Lossless antenna gain (dBi)	22.40
Solar Flux at 432 MHz (SFU)	44.0
Tx power at antenna (W)	100
EME path loss (dB)	261.6
G/Ta (dB/K)	5.5
G/Ts (dB/K)	1.6
Y Sun (dB)	9.9
EME S/N in B=2500 Hz (dB)	-23.0
EME S/N in B=50 Hz (dB)	-6.0

JT65 Weak Signal Protocol

MarCO (6U, 10cm x 20cm x 34cm, 14kg) with 4 W Iris-2 X-Band (9 GHz) Radio, relay for InSight, 60 cm × 34 cm antenna, >28 dB gain (1m dish is 37 dB) 2,040 cm^2

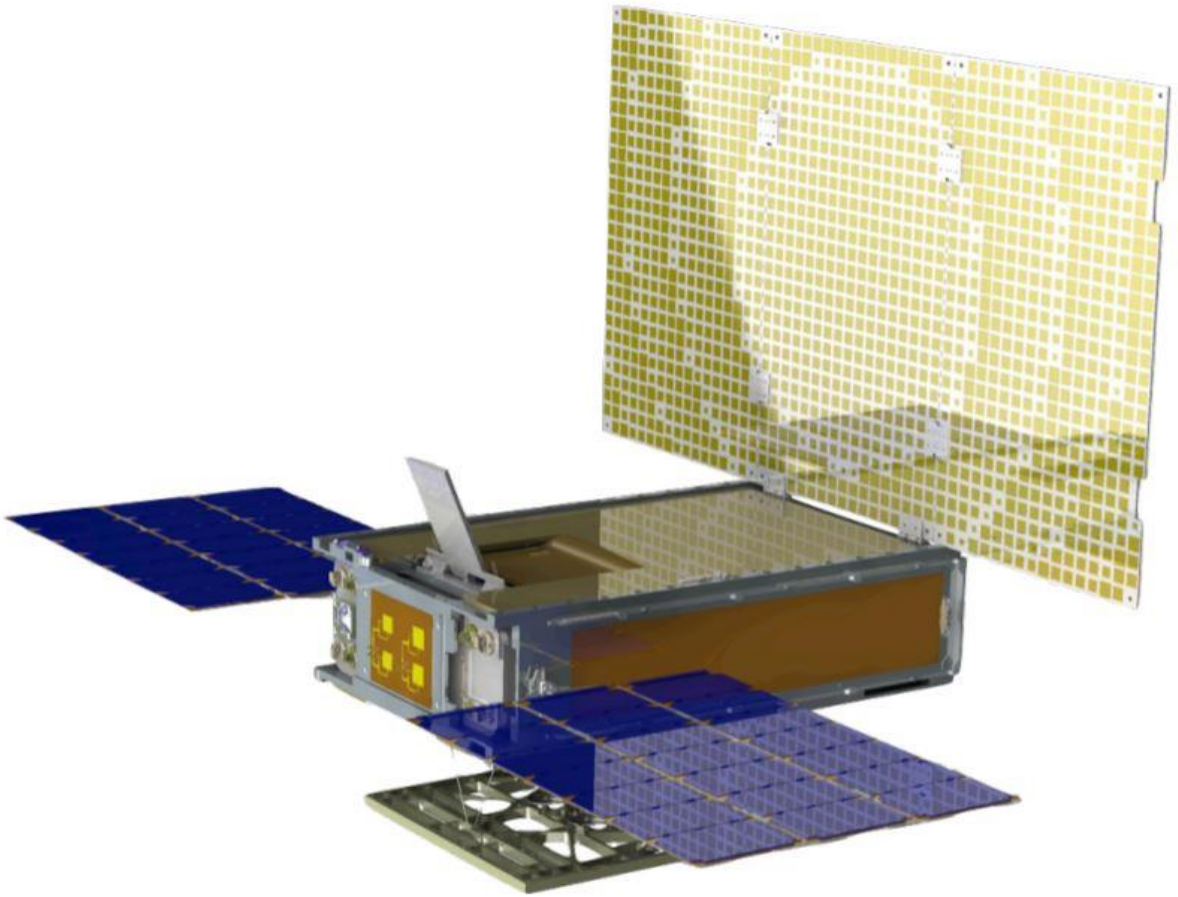
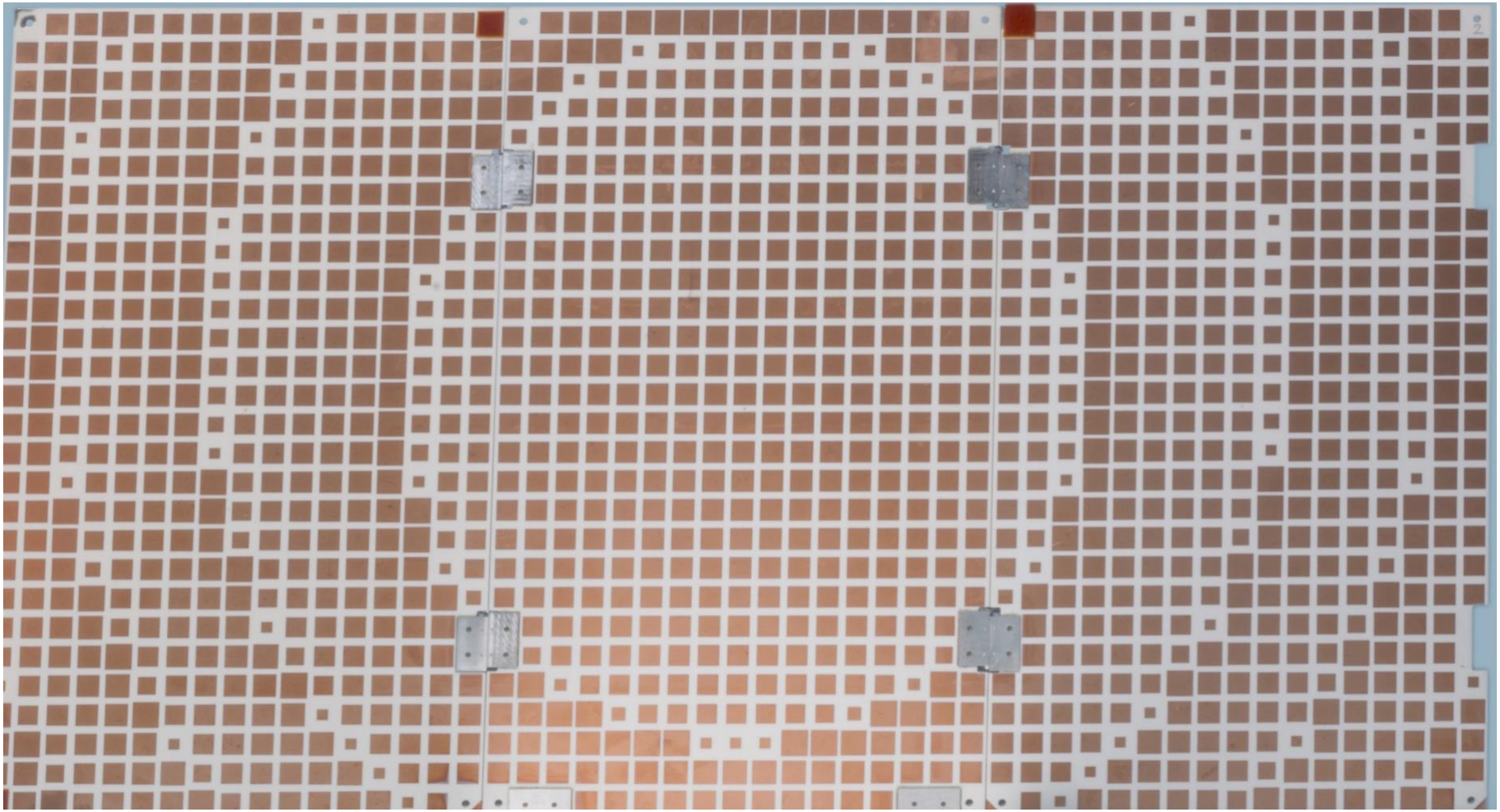


Figure 1 – CAD model rendering of a MarCO CubeSat. The large vertical panel is the high-gain reflectarray, capable of transmitting 8 kbps from Mars to the Deep Space Network's 70m dish in Madrid, Spain.

JT65 Weak Signal Protocol

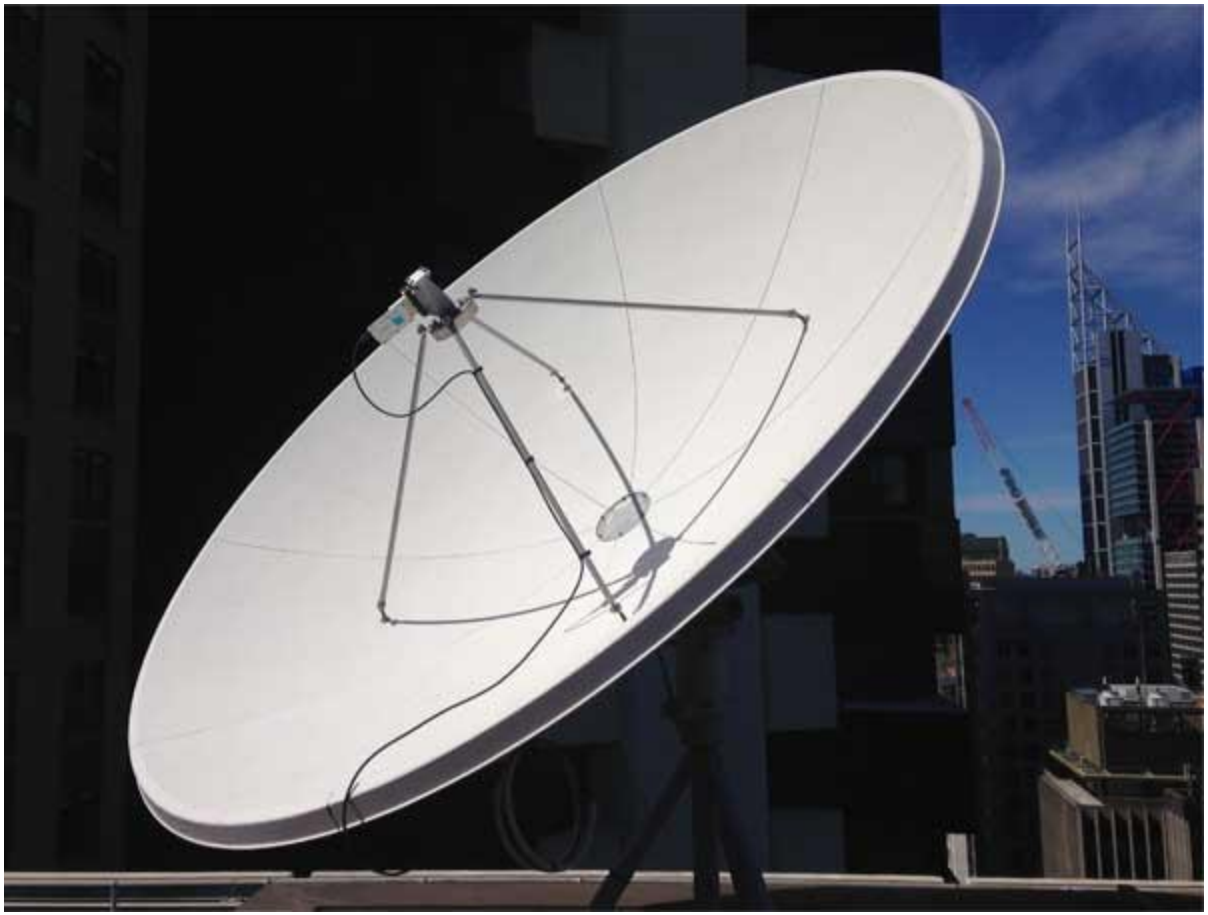
The Mars Cube One deployable high gain reflectarray antenna, https://ieeexplore.ieee.org/document/7696473

60 cm × 34 cm antenna, >28 dB gain (1m dish is 37 dB) 2,040 cm^2



JT65 Weak Signal Protocol

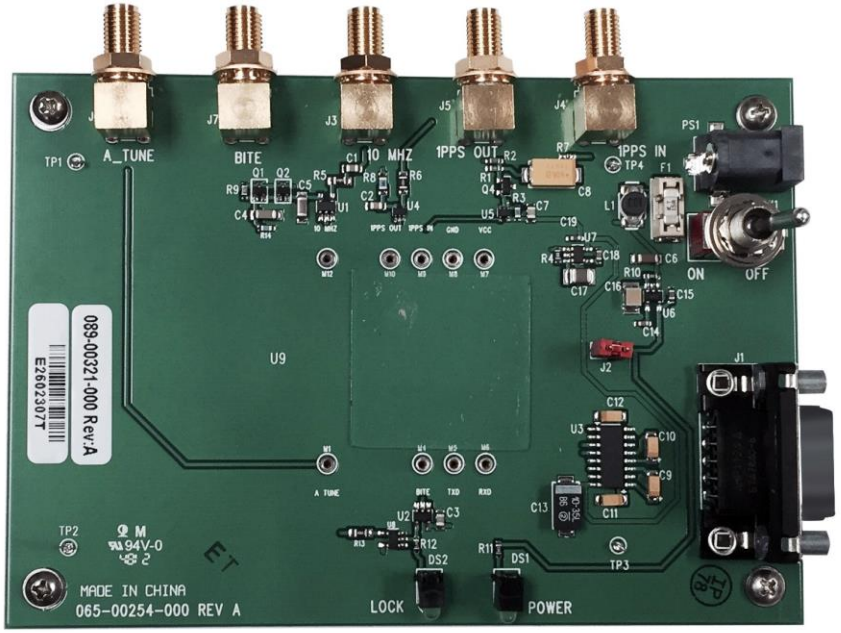
Allows the use of a 3m dish university ground station instead of the 70 m DSN



JT65 Weak Signal Protocol

- We just started a NASA grant to test JT-65 for deep space CubeSat use
- 70 cm band will be used as X-band transceivers cost 10x as much
- Moon bounce will be used for testing
- Moon bounce path loss, 262 dB
- Straight line to Jupiter path loss, 262 dB
- Although data rate is slow, 24 hour use would allow 50.6 kB per day, 20 days/MB

In using JT-65 when away from the Earth, timing from GPS is not available. We will be using the Microsemi SA.45s Chip-Scale Atomic Clock.



Development Board **Clock Chip**

This cesium atomic clock in a 4.0 cm x 3.5 cm x 1.1 cm package is accurate to about 10 ms per year.

Flight Software based on *CubedOS*

- *Intended to be a general purpose framework for CubeSat flight software*
- Written **in SPARK**; proven free from runtime errors
- Provides inter-module message passing framework
- Provides services of interest to flight software
- Can integrate existing Ada or C runtime libraries
- *Conceptually similar to NASA's cFE/CFS except written in SPARK (not C).*
- Non ITAR parts on GitHub, https://github.com/cubesatlab/cubedos & merc
- ITAR parts from us (currently Spiral Thrusting)

CubedOS Verification Goals

- No flow errors
- Show freedom from runtime error
- Other correctness properties as time allows

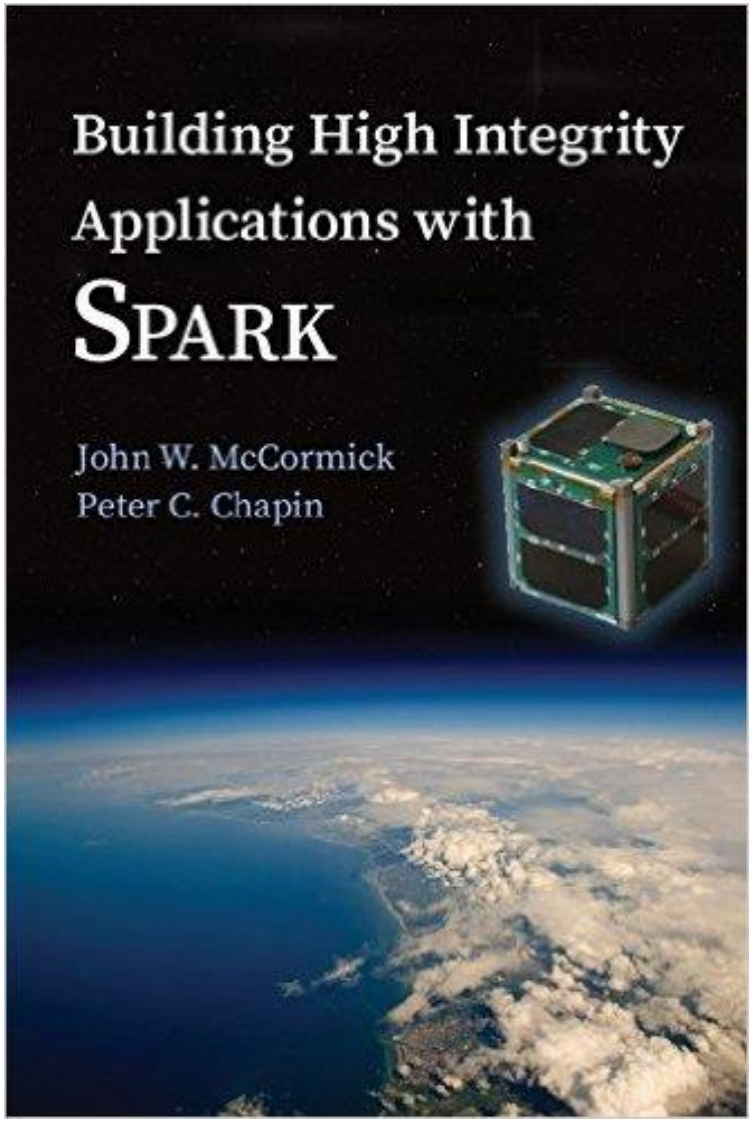
CubedOS Testing

- Unit tests
- Some additional test programs (x86)
- Hardware development system (PowerPC)

Why not NASA's cFE/CFS?

- "cFE/CFS" = "Core Flight Executive / Core Flight System"
- Similar architecture
  - Uses publish/subscribe (not point-to-point)
  - Uses CCSDS space packets for messages
- cFE written in C. Not verified
- We hope to eventually offer CubedOS as a competing SPARK platform for spacecraft software
- possible CubedOS/CFS bridge that will translate messages between the systems

A SPARK 2014 Book is Available



Revised edition being written now.

Vermont's First Astronaut

Acknowledgements

- NASA Vermont Space Grant Consortium
- Vermont Technical College
- AdaCore, Inc. (GNAT Pro, SPARK Pro)
- Applied Graphics, Inc. (STK)
- Busek (BIT-3 Iodine ion drive)
- NASA Jet Propulsion Lab (Iris-2 Radio)

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